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Investigation of the Notch Sensitivity of Nickel-Copper-Aluminum (K-Monel) Rod

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MEL R&D Report 309/65
Sub-Project S-R007 09 02
Task 0857
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ABSTRACT

Tensile and notch tensile properties of K-monel processed by different fabrication techniques were investigated. Material processed by standard hot rolling and cold drawing was found to meet the ductility and strength requirements of military specifications. A drastic (30%) final cold reduction, followed directly by aging, lowered the percent of elongation below requirements of military specifications, but did not lead to weakness or brittleness of notched specimens. Extruding of small ingots with insufficient reduction of area led to material with low strength and brittleness.

ADMINISTRATIVE INFORMATION

This is the final report of an investigation authorized by Bureau of Ships letter R007 09 02 Serial 634B-734 of 2 August 1963. The Sub-project number is S-R007 09 02, Task 0857.

TECHNICAL REFERENCES

1 - Kondratenko, W., "Tensile, Chemistry and Microstructure of Some Rejected K-Monel Studs," General Dynamics/Electric Boat Div., Project M-1101B, U413-64-060, 27 Mar 1964
2 - Lovelace, J. F., Luini, L. A., and Cook, D. T., "Eddy Current Non-Destructive Test Method for K-Monel," Final Report, Contract NObs-90038 (FBM), 9 Dec 1964
3 - Fed Spec QQ-N-286a, 29 Jul 1954, and Amend. 1, 1 Aug 1956
4 - Fourth Report of a Special ASTM Committee, "Screening Tests for High Strength Alloys Using Sharply Notched Cylindrical Specimens," Materials Research and Standards, Mar 1962
5 - Mil Spec MIL-B-857A(SHIPS), Amend. 4, 15 Dec 1964, p. 9
6 - Mil Std MS 18116(SHIPS), 15 Jun 1964

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INVESTIGATION OF THE NOTCH SENSITIVITY OF NICKEL-COPPER-ALUMINUM (K-MONEL) ROD

1.0 INTRODUCTION

K-monel, which is used by the U. S. Navy as a fastener material in ship construction has occasionally been reported to have low ductility.[1] Brittle fracture of such fasteners, especially when used in hull integrity applications in submarines, could be catastrophic.

1.1 Background. An investigation of the notch sensitivity of K-monel, processed and heat treated several different ways, was initiated at this Laboratory to evaluate the conditions that may cause embrittlement. In addition to commercial hot rolling and cold drawing of K-monel, the process and material variables investigated were (a) the effect of a large (30%) final cold-drawing reduction, (b) the effect of varying hot-rolling temperature during rolling of small ingots, (c) the effect of extrusion instead of hot rolling or cold drawing, (d) the effect of aluminum content in K-monel, and (e) the effect of heat treatment on all of the different starting materials. Notched and unnotched tensile data were obtained for each material, and specimen size and notch sharpness were also varied.

1.2 Scope. In addition to the laboratory study, MEL was assigned the task of monitoring BUSHIPS Contract NObs-90038 (FBM) carried out by the Electric Boat Division of General Dynamics Corporation. Under this contract the feasibility of developing electrical eddy-current methods for evaluating the ductility of K-monel fasteners and for nondestructive "in-place" examination was explored. It was concluded that the eddy-current test could not be used reliably to predict acceptable or rejectable ductility in K-monel. The details of this work were covered in a final report issued by Electric Boat.[2]

[1] Superscripts refer to similarly numbered entries in the Technical References at the beginning of this report.

2.0 MATERIAL DESCRIPTION

The K-monel was obtained from the International Nickel Company, Incorporated (INCO). The nominal composition and the range of compositions encountered in the alloys investigated are listed below.

Composition of Materials, Weight Percent

	C	Mn	Fe	S	Si	Al	Ti	Ni	Cu
Nominal Composition (Reference 3)	0.25 max	1.5 max	2.0 max	0.010 max	1.0 max	2.0-4.0	0.25-1.00	63.0-70.0	bal
Range of Composition of Alloys Investigated	0.12-0.19	0.48-0.68	0.60-1.25	0.003-0.009	0.09-0.28	2.00-4.04	0.44-0.55	63.4-65.9	28.5-31.3

max - maximum bal - balance

In studying the effect of hot-rolling temperature, an attempt was made to roll below the normal range of 1600-2100 F.* However, rolling at 1500 F caused damage to the rolls, so that no material was obtained.

*Abbreviations used in this text are from the GPO Style Manual, 1959, unless otherwise noted.

2.1 Processing. The extrusion billets were melted by INCO and extruded at the DuPont Metals Center. The billets were 6 inches in diameter, 10 inches in length, and weighed about 80 pounds. They were extruded to 2-inch-diameter bar stock, a reduction in cross-sectional area of approximately 9 to 1. The aluminum content varied from 2.00 to 4.04 weight percent. Attempts to hot roll K-monel containing 4-percent aluminum were unsuccessful because the material was too brittle; however, alloys of this aluminum content could be processed by extrusion.

2.2 Symbols. Symbols have been used throughout this report for ease in indentification of the production methods and of the heat treatments used by MEL on the various as-received materials. These symbols are defined as follows:

Symbol	Description
	Production Methods
HR	Hot rolled; stock item.
HR at X°F	Hot rolled specifically for this program at indicated temperature.
CD	Cold drawn; stock item.
30% CD	Cold drawn specifically for this program with a final pass of 30-percent reduction in area.
Extrusion at X°F	Extruded specifically for this program at indicated temperature.
	Heat Treatments
A	Aged 16 hours at 1080-1100 F; furnace cooled to 900 F at 15-25 F per hour followed by air cooling; this is the standard aging treatment for K-monel to give maximum properties.
B	Annealed at 1700 F for 15 minutes and water quenched followed by aging outlined for A.
C	Aged at 1300 F for 12 hours and furnace cooled to 900 F at 15-25 F per hour followed by air cooling; this heat treatment results in overaging.

Heat Treatments (Cont)

AA	Same as A except aging time changed to 10 hours.
CC	Same as C except aging at 1250 F for 10 hours.

3.0 EXPERIMENTAL PROCEDURE

Smooth and notched bar tensile specimens of the different materials were evaluated. Most of the specimens were standard ASTM 0.505-inch-diameter bars, which for the notched tensile tests contained a 50-percent 60-degree V-notch with a root radius varying between 0.001 and 0.004 inch. When specimen size and notch sharpness were the principal variables, the dimensions were scaled up from the standard 0.505-inch bar. The 1.875-inch-diameter notched specimens were cracked by fatigue to increase notch acuity to a radius reported to be from 0.0003-0.0007 inch.[4] This was accomplished by rotating the specimen in a low rpm cantilever machine under a stress between 30 and 60 percent of the yield strength of the material.

4.0 RESULTS

Mechanical properties were judged acceptable or nonacceptable according to the most recent military specifications available for K-monel bolts and studs.[5,6] These call for a minimum tensile strength of 130,000 psi, minimum yield strength (0.2% offset) of 90,000 psi, and minimum elongation (in 2 inches) of 20 percent. Federal material specifications call for about 10-percent higher yield and tensile strengths, but permit minimum elongation values between 15 and 20 percent (depending on size) for cold-drawn and aged material.[3]

4.1 Tensile Tests of 0.505-Inch-Diameter Specimens. Results of notched and unnotched tensile tests for all materials using 0.505-inch-diameter specimens are listed in Appendix A, page A-1. The data are summarized in Figures 1, 2, and 3.

Figure 1 is a plot of notch strength versus tensile strength for bar stock produced by standard procedures of hot rolling or cold drawing followed by specific heat treatments (A, B, or C). The data fell into three groups according to heat treatment.

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O Aged, Heat Treatment A
+ Annealed and Aged, Heat Treatment B
Δ Overaged, Heat Treatment C
Numbers are Percent Elongation of Unnotched Specimens
NSR - Notch Strength Ratio

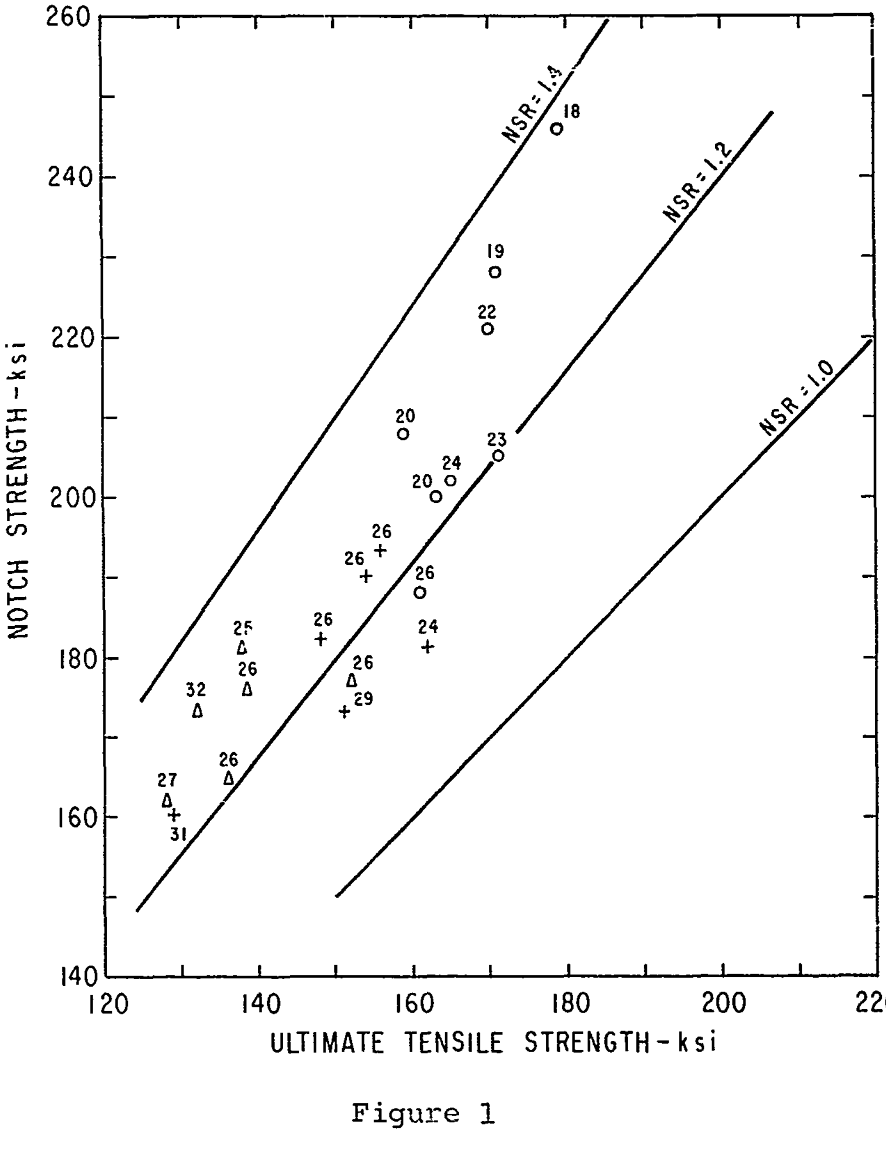

Figure 1

Notch Strength Vs Tensile Strength for 0.505-Inch Specimens Machined from Standard Hot Rolled or Cold Drawn Stock

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o Aged, Heat Treatment A
+ Annealed and Aged, Heat Treatment B
Δ Overaged, Heat Treatment C
Numbers are Percent Elongation of Unnotched Specimens
NSR - Notch Strength Ratio

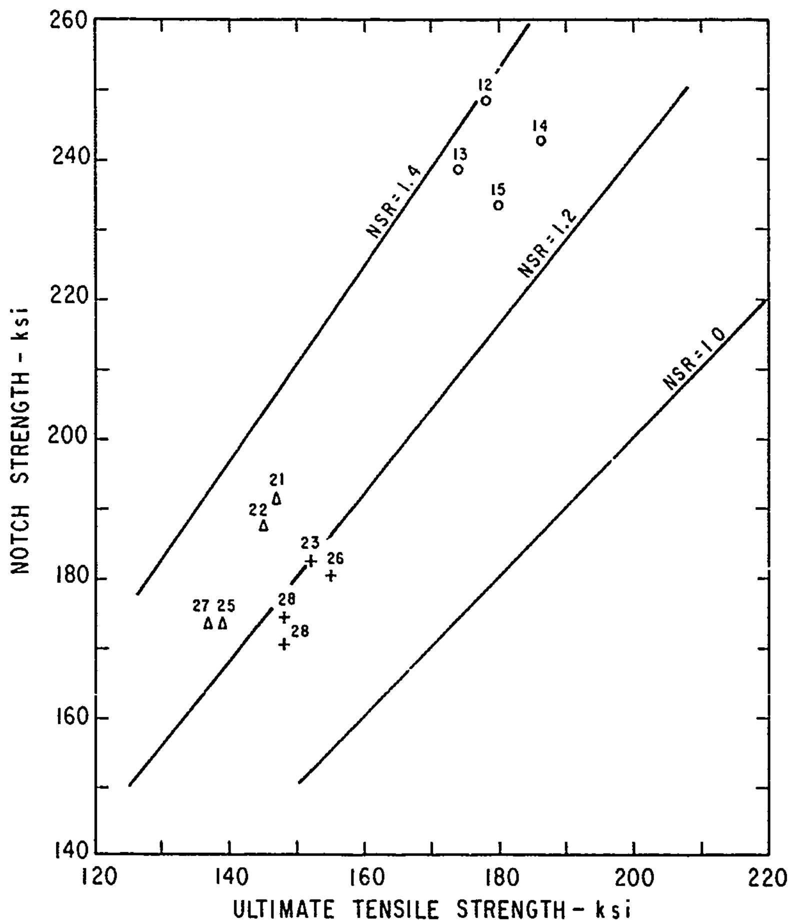

Figure 2

Notch Strength Vs Tensile Strength for 0.505-Inch Specimens Machined from Stock Cold Drawn with a Final Pass of 30-Percent Reduction in Area

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O Aged, Heat Treatment A
+ Annealed and Aged, Heat Treatment B
Numbers are Percent Elongation of Unnotched Specimens
NSR - Notch Strength Ratio

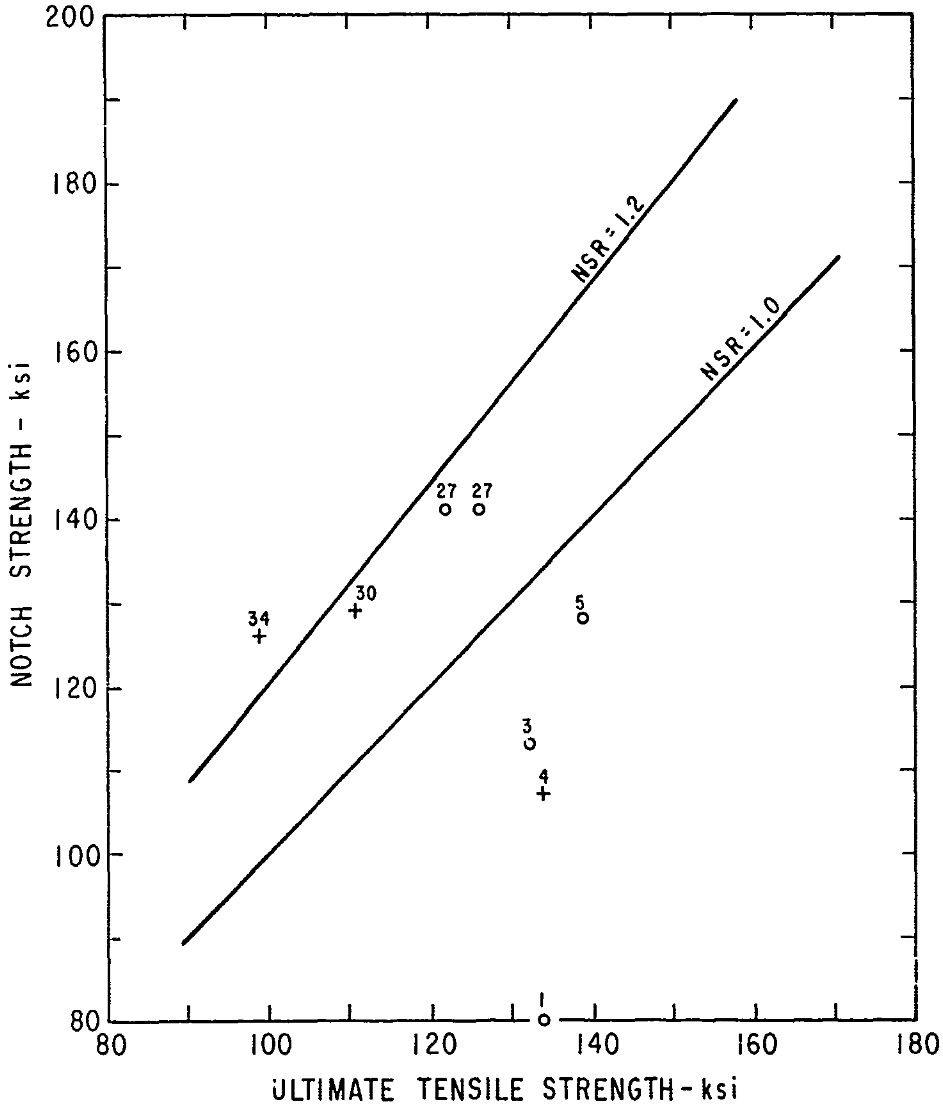

Figure 3

Notch Strength Vs Tensile Strength for 0.505-Inch Specimens
Machined from Extruded Stock

The highest tensile and notched tensile strength and lowest elongation were obtained with material aged as received from the supplier. Lower strength and higher elongation were obtained on material that was annealed prior to aging. The lowest tensile strength and highest elongation were obtained by overaging.

Examination of the data in light of the most recent military specifications shows that all specimens met the strength and ductility requirements with the following exceptions. Two specimens had elongation values just below the required minimum of 20 percent. These two specimens had the highest notched and unnotched tensile strength and had been machined from bar stock produced by cold drawing followed by aging. It is this condition for which the minimum elongation required in federal specifications is only 15 percent for bar stock up to 1-inch diameter.[3] Two different specimens, one annealed and aged and the other overaged, had tensile strengths slightly below the required 130,000 psi (129,000 and 128,000 psi, respectively).

Notch-strength ratios, defined as the ratio of notched strength to ultimate tensile strength, are likewise shown in Figure 1. Most of the specimens had ratios between 1.2 and 1.4.

About 30 additional test results are listed in Appendix A on standard material with slightly different heat treatments (AA and CC). These results showed no significant deviations from those reported in Figure 1. Five of the specimens, cold drawn and aged without intermediate anneal, had elongation values of 18 or 19 percent instead of the required 20 percent.

Figure 2 presents similar data for material produced by cold drawing with a final pass of 30-percent reduction in area. Aging the "as-received" material again resulted in the highest strength and lowest elongation, the latter varying between 12 and 15 percent. The annealed and aged as well as the overaged specimens had tensile strengths above the 130,000 psi minimum and elongations greater than 20 percent. The overaged specimens, however, generally had yield strengths below the 90,000 psi specified in military specifications.[5,6]

A total of 20 notched and unnotched specimens of material produced by extrusion were tested, and the data are shown in Figure 3. The difference in scale compared to Figures 1 and 2 should be noted. None of the specimens gave satisfactory results. The specimens either had low strength and sufficient elongation, or strengths

just above 130,000 psi with very low ellongation. The lack of toughness is illustrated by the low notch-strength ratios shown in Figure 3. No correlation was found between tensile properties and extrusion temperature, but ductility varied with aluminum content. Specimens containing 2.00- and 2.09-percent aluminum had high elongation but low strength; specimens containing 2.97-, 3.12-, 3.89-, or 4.04-percent aluminum had very low elongation, low notch strength, and marginal tensile strength.

Several test results in Appendix A are reported on small billets hot rolled at a specific temperature. The results indicated that low aluminum content (2.00%) resulted in satisfactory strength and ductility, and intermediate aluminum content (2.97%) resulted in elongation values of 8 to 10 percent in the aged condition. Small billets containing high aluminum (about 4%) could not be hot rolled.

4.2 Tests Showing Effects of Specimen Size. The effect of specimen size (up to 2 inches in diameter) on notch tensile strength is shown in Figure 4. The data are listed in Appendix A, pages A-2 and A-3. Most of the 1.875-inch diameter specimens had machined notches with a fatigue crack, whereas all other specimens had machined notches only.

The lines drawn in Figure 4 represent trends which indicate a relatively small decrease in notch strength due to an increase in specimen size. The number of specimens available was insufficient to establish the exact shape of the curves.

The highest notch strength across the specimen size range was exhibited by the material cold drawn with a final pass of 30-percent reduction in area and heat treated to maximum hardness (Heat Treatment A). It is of interest that this material had a tensile elongation of only 14 percent in the 0.505-inch-diameter unnotched tensile tests. The effect of annealing prior to aging (Heat Treatment B) on the level of notch strength is marked as shown for the same material in Figure 4.

Comparison of the commercially hot-rolled and cold-drawn materials, heat treated to maximum hardness, shows that both have about the same notched tensile strength for 0.505-inch-diameter specimens, but that strength drops off more rapidly with specimen size for the cold-drawn material.

The data shown for the extrusions are for material with aluminum contents of 2.00 and 2.09. These are the two alloys that exhibited low strength but high elongation in Figure 3. Six tests were attempted with extruded alloys of higher aluminum content (very low elongation and low strength). All had a 1.875-inch test diameter. Of these, two fractured during fatigue cracking; two split during machining or fractured in the test grips; and two gave notched strength values of 63,000 and 40,000 psi.

4.3 Examination of Fractured Surfaces. Figures 5 and 6 show some of the fractures of the 1.875- and 2.000-inch-diameter specimens. The top three fractures in Figure 5 are of material produced by standard commercial hot-rolling or cold-drawing procedures and are typical of all materials produced this way. The bottom three fractures in Figure 5 are of material cold drawn with a final pass of 30-percent reduction in area. The specimen on the left broke during fatigue cracking. The other two specimens were tested after fatigue cracking, and the depth of the fatigue crack is visible on the outer periphery of the fracture surface. Some internal cracks were noted in these two specimens.

Figure 6 shows the fracture surface of four extruded specimens. These had a much coarser texture than the standard specimens shown in the top row of Figure 5. The specimen on the right, which broke during fatigue cracking, represented the most extreme case.

4.4 Microstructural Examination. Figure 7 contains represntative microstructures of a number of specimens after aging by Heat Treatment A. Items (a) and (b), Figure 7 show the standard hot-rolled and cold-drawn structures, respectively. The grain size of the hot-rolled material was found to be more uniform than for the cold-drawn material which was subject to some banding of fine and coarse grains. Item (c), Figure 7, by comparison, is the structure of the material cold drawn with a final pass of 30 percent. A very large grain size was observed compared to the structures in Items (a) and (b), Figure 7.

The structure of an extruded specimen containing 2-percent aluminum is shown in Item (d), Figure 7. All of the extruded specimens contained very pronounced flow lines in the extrusion direction, and grain size varied with extrusion temperature.

Figure 8 shows the structure of a high aluminum content extruded alloy (3.89% aluminum) after Heat Treatment B.

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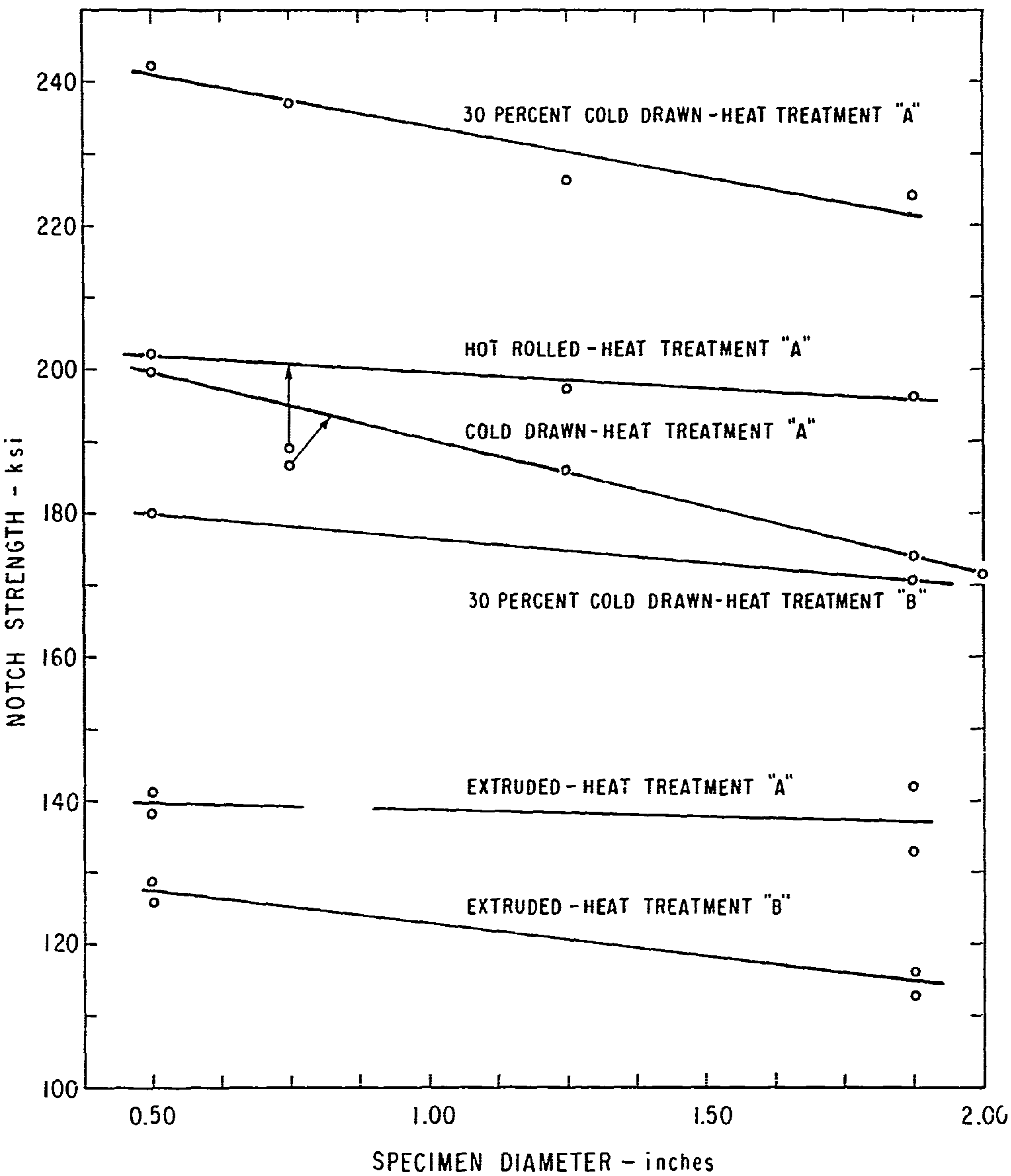

Figure 4

Notch Strength vs Specimen Diameter for Various K-Monel Specimens

This alloy, representing a brittle composition compared to the alloy in Item (d), Figure 7, was characterized by very heavy flow lines, intercrystalline cracking, and voids.

5.0 DISCUSSION

5.1 Material Processed by Standard Practice. The data obtained on material produced by commercial practice of hot rolling or cold drawing indicates that neither condition results in embrittlement of K-monel. A total of fifty 0.505-inch-diameter specimens, varying in aluminum content from 2.55 to 3.21 percent and tested after different heat treatments, showed no evidence of brittle behavior. Seven of the specimens had elongation values below the 20 percent required by military specifications, but no values below 18 percent were recorded. Of the seven specimens, six were machined from material cold drawn and heat treated to maximum hardness (Heat Treatment A). This is not surprising when one considers that hot rolling is the process normally used for alloy breakdown, while cold drawing is used primarily to achieve high tensile strength, usually associated with a drop in ductility.

The good general performance of hot-rolled or cold-drawn material was confirmed by (a) the small decrease in notch strength with section size (Figure 4), (b) notch-strength ratios of 1.2 to 1.4, (c) ductile-looking fractures of large specimens (Figure 5), and (d) relatively clean microstructures without indications of cracking (Items (a) and (b), Figure 7).

5.2 Material Processed with Variation from Standard Practice. The principal variation in standard practice was a 30-percent final reduction during cold drawing. This did not effect a change from ductile to brittle behavior, but did decrease ductility in the fully aged condition (Heat Treatment A) to the 12- to 15-percent elongation level. The notch strength of this material with increasing specimen diameter remained high, as shown in Figure 4. Annealing prior to aging (Heat Treatment B) eliminated the effect of the cold work and resulted in properties that were similar to those of the standard material.

5.3 Material Processed by Extrusion. The extrusion of K-monel produced generally poor structures and resulted in complete brittleness at the higher aluminum contents. The most obvious reason for this would appear to be an insufficient amount of hot work inherent in working a small billet.

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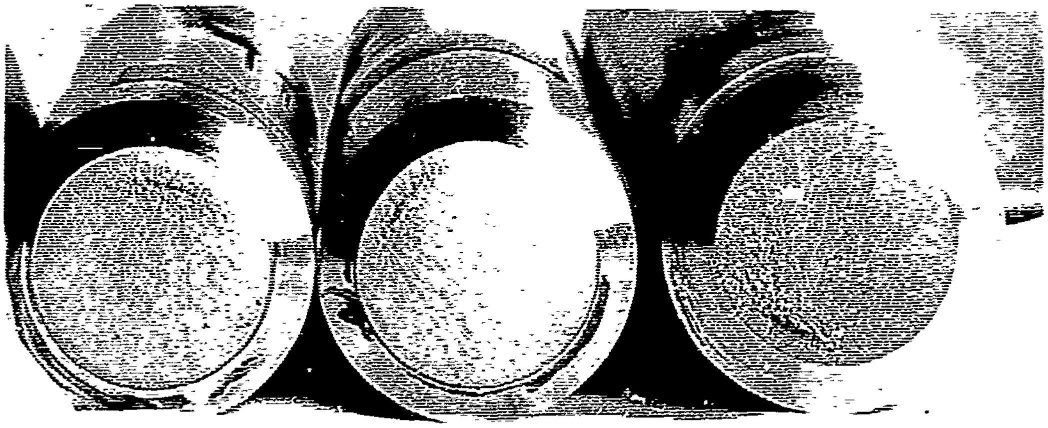
Material Code:	DZL	DZS	DZS
Production:	Hot Rolled	Cold Drawn	Cold Drawn
Heat Treatment:	A	A	A
Notch Strength:	196,000 PSI	174,000 PSI	171,000 PSI



Material Code:	EAH	EAH	EAH
Production:	← 30-Percent Cold Drawn →		
Heat Treatment:	C	A	B
Notch Strength:	Broke in Fatigue	224,000 PSI	171,000 PSI

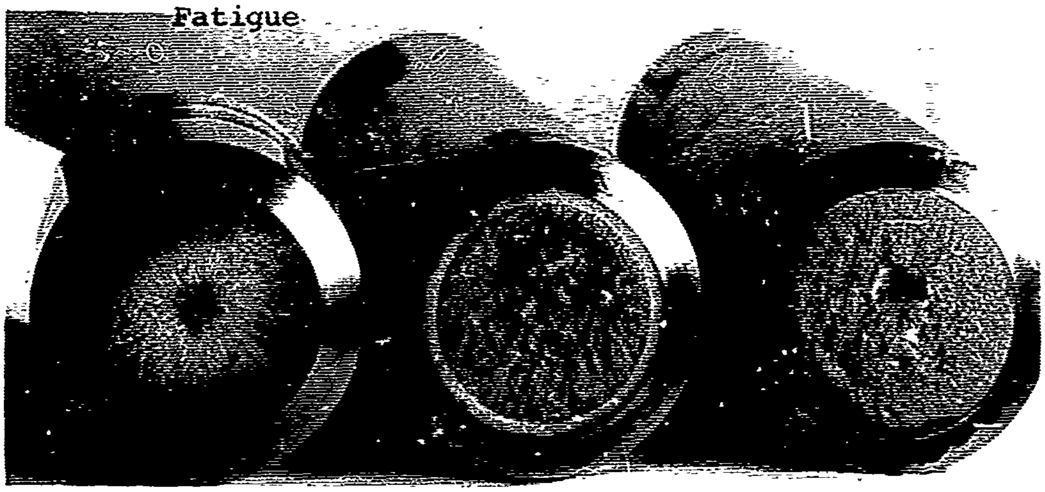


Figure 5

Fracture Surfaces of K-Monel Specimens

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	Material Code		
EBO	EBP	EBP	EBR
	Production		
Extruded at 1700 F	Extruded at 1800 F	Extruded at 1800 F	Extruded at 1800 F
	Heat Treatment		
A	A	B	A
	Notch Strength		
63,000 PSI	Broke in Fatigue	40,000 PSI	Broke in Fatigue

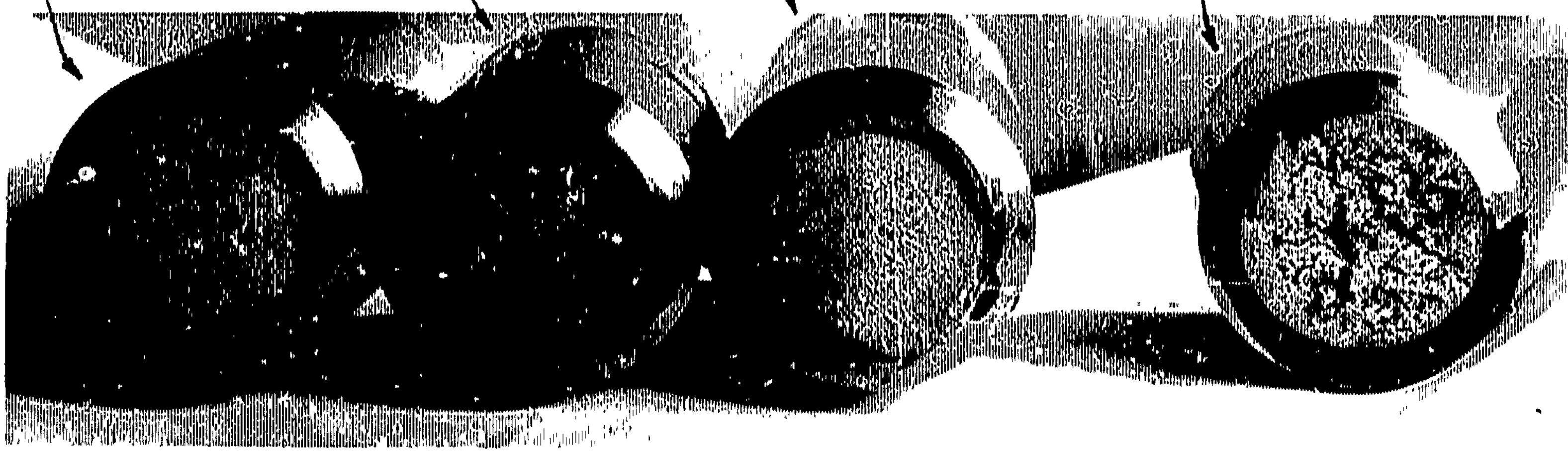
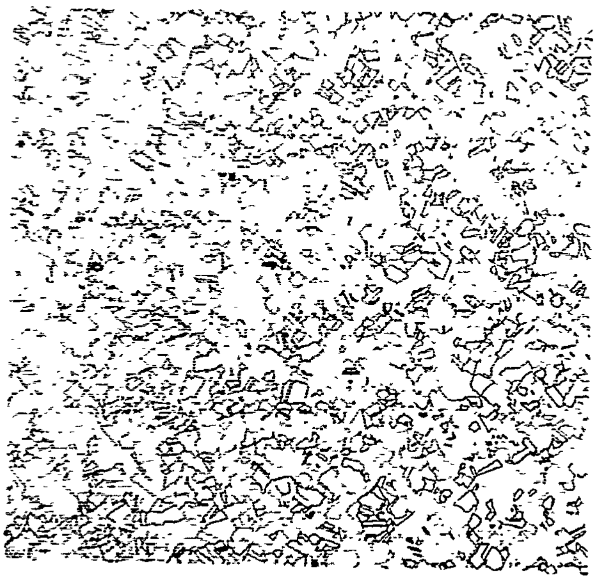


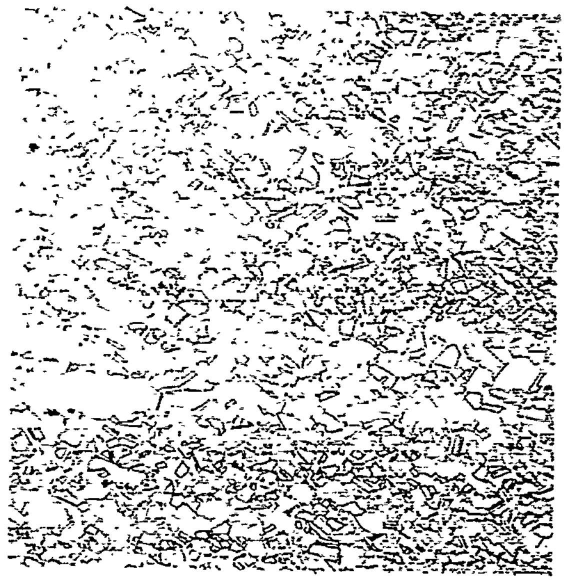
Figure 6

Fracture Surfaces of Extruded K-Monel Specimens

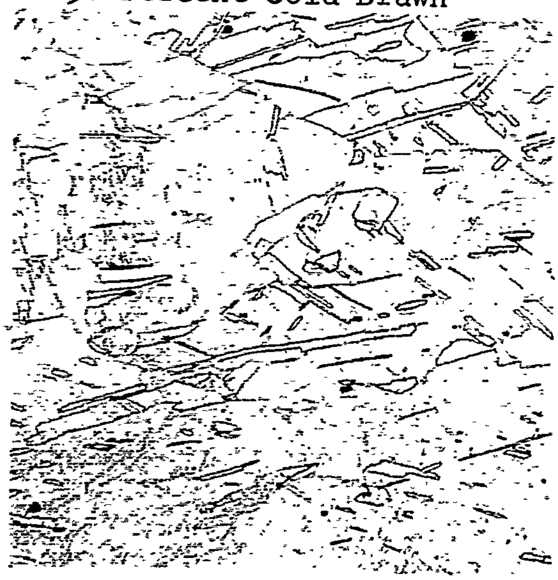
Item (a) - Material Code DZZ
Hot Rolled



Item (b) - Material Code DZR
Cold Drawn



Item (c) - Material Code EAI
30-Percent Cold Drawn



Item (d) - Material Code EBM
Extruded at 2000 F

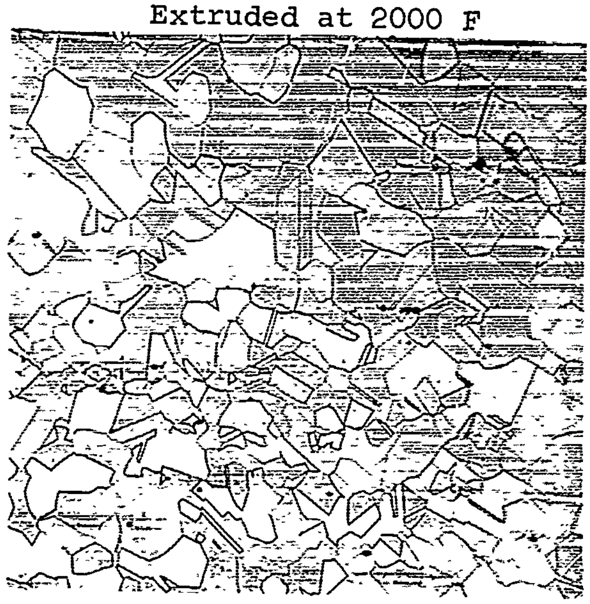


Figure 7

Microstructures of Aged K-Monel Specimens (Heat Treatment A),
Longitudinal Section, $FeCl_3$ Etch (100X)

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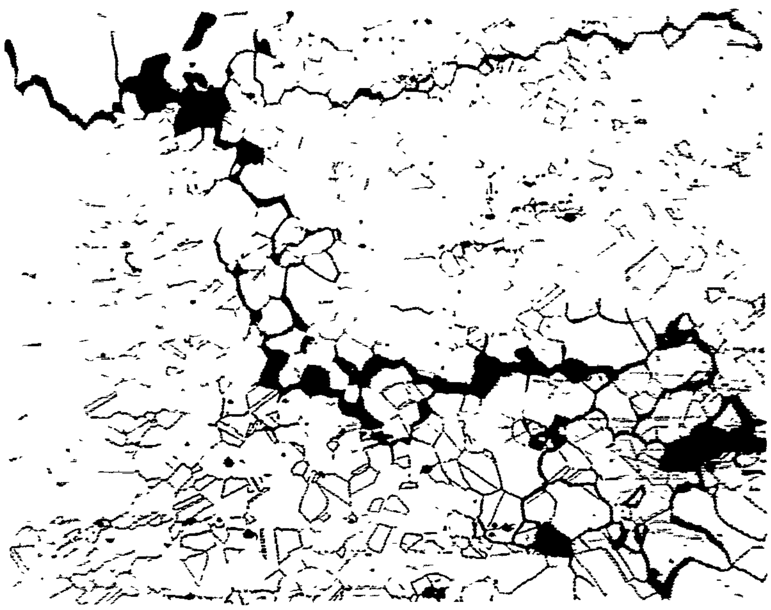

Figure 8
Microstructure of Extruded K-Monel Specimen,
Annealed and Aged (Heat Treatment B), Longitudinal Section, $FeCl_3$ Etch, Material Code EBQ (100X)

The normal breakdown procedure for wrought products is by hot working from an ingot no less than 14 inches square. By comparison, the extrusion billets were about 6 inches in diameter. Assuming a final diameter of 2 inches, the cross-sectional area reduction would be at least 62 times for a commercial ingot compared to 9 times for the experimental extrusions.

The heavy flow lines retained in the extruded billets, even in the recrystallized condition, appear to be further evidence of inhomogeneity. In this connection, it should be pointed out that specimens having a diameter less than 2 inches were machined out of 2-inch extruded stock, so that the smaller specimens did not contain any additional work.

5.4 Effect of Aluminum Content. Since the extruded specimens containing 2.00- and 2.09-percent aluminum were ductile, and specimens containing 2.97-, 3.12-, 3.89-, and 4.04-percent aluminum were brittle, the question arises as to the effect of aluminum content on embrittlement. Extruded alloys containing 2.97- and 3.12-percent aluminum were compared to standard material with aluminum contents from 2.92 to 3.21 percent. Three 0.505-inch-diameter extruded specimens had elongations of 3, 4, and 5 percent, while 20 standard specimens had elongations ranging from 18 to 31 percent. Therefore, embrittlement cannot be attributed solely to aluminum content, although the embrittlement resulting from lack of hot work became increasingly severe with higher aluminum content. The extruded specimens containing 3.89- and 4.04-percent aluminum had practically zero ductility.

The aluminum content of the standard materials varied between 2.55 and 3.21 percent. Analysis of 50 tensile tests showed no trend in elongation with aluminum content.

6.0 CONCLUSIONS

- Standard fabrication techniques for K-monel (by hot rolling and cold drawing followed by aging) do not result in embrittlement.

- Material finished by standard cold drawing and aged to maximum hardness sometimes falls just short of the 20-percent elongation required by military specifications. One series of specimens, however, in which the final pass was increased deliberately to 30-percent reduction in area (considerably greater than

normally employed), followed by aging to maximum hardness, had elongation values of 12 to 15 percent. No discontinuous change in ductility was encountered.

- Annealing prior to aging results in a combination of properties most likely to meet military specifications for all materials fabricated by standard techniques.

- The use of small billets or ingots as the starting material for further fabrication should be avoided.

- Extrusion of small ingots with a 9 to 1 reduction ratio results in generally brittle material as evidenced by the impossibility of machining alloys of higher aluminum content into test specimens.

Appendix A

Tensile and Notch Tensile Data for K-Monel Specimens

Table 1

Notched and Unnotched Tensile Test Results for 0.505-Inch-Diameter Specimens

Material Code	Fabrication[1]	Heat Treatment[1]	Aluminum WT %	NS ksi	US ksi	YS (0.2% Offset) ksi	Elong % in 2 in.	Red. in Area %	Hardness R_C	Notch-Strength Ratio[2]
DZL	HR	A	2.92	202	165	123	24	40	-	1.22
DZM	HR	A	2.78	188	161	110	26	41	38	1.16
DZM	HR	C	2.78	177	152	100	26	43	31	1.16
DZM	HR	B	2.78	160	129	72	31	56	27	1.24
DZP	CD	A	2.88	208	159	127	20	40	36	1.31
DZP	CD	B	2.88	182	148	102	26	47	31	1.22
DZP	CD	C	2.88	162	128	85	27	54	22	1.26
DZQ	HR	A	2.77	221	170	126	22	32	36	1.30
DZQ	HR	B	2.77	193	156	108	26	47	30	1.24
DZQ	HR	C	2.77	173	132	84	32	57	25	1.31
DZR	CD	A	2.96	228	171	140	19	40	36	1.33
DZR	CD	B	2.96	173	151	94	29	47	29	1.15
DZR	CD	C	2.96	180	138	92	25	56	27	1.32
DZS	CD	A	2.93	200	163	125	20	35	-	1.23
DZT	CD	A	2.77	246	179	158	18	45	37	1.37
DZT	CD	B	2.77	190	154	102	26	43	26	1.24
DZT	CD	C	2.77	176	139	91	26	54	24	1.27
DZZ	HR	A	2.88	205	171	123	23	39	37	1.20
DZZ	HR	B	2.88	181	162	110	24	33	32	1.12
DZZ	HR	C	2.88	165	136	83	26	51	26	1.21
EAH	30% CD	A	2.78	242	186	157	14	23	-	1.30
EAH	30% CD	B	2.78	180	155	99	26	39	30	1.16
EAH	30% CD	C	2.78	187	145	102	22	53	-	1.29
EAI	30% CD	A	2.67	238	174	147	13	21	36	1.36
EAI	30% CD	B	2.67	174	148	89	28	50	28	1.18
EAI	30% CD	C	2.67	173	137	82	27	53	23	1.27
EAJ	30% CD	A	2.68	248	178	155	12	33	37	1.39
EAJ	30% CD	B	2.68	182	152	97	23	49	30	1.20
EAJ	30% CD	C	2.68	173	139	88	25	53	25	1.25
EAK	30% CD	A	2.87	233	180	149	15	30	38	1.29
EAK	30% CD	B	2.87	170	148	91	28	50	30	1.15
EAK	30% CD	C	2.87	191	147	107	21	50	32	1.30
EAL	HR at 2100 F	A	2.00	172	139	90	30	51	23-27	1.24
EAN	HR at 1700 F	A	2.00	171	140	96	28	50	28	1.22
EAO	HR at 2100 F	A	2.97	149	150	114	10	12	32	0.99

[1]Fabrication and heat treatment symbols are listed in text of this report.
[2]Notch-strength ratio = notch strength/ultimate strength.

ksi - thousand pounds per square inch
NS - Notched Strength
US - Ultimate Strength
YS - Yield Strength
Elong - Elongation
Red. - Reduction
WT - Weight

Table 1 (Cont)

Material Code	Fabrication[1]	Heat Treatment[1]	Aluminum WT %	NS ksi	US ksi	YS (0.2% Offset) ksi	Elong % in 2 in.	Red. in Area %	Hardness R_C	Notch-Strength Ratio[2]
EAM	HR at 1850 F	A	2.97	145	143	112	8	10	3	1.02
EBM	Ext at 2000 F	A	2.00	141	122	72	27	51	23	1.16
EBM	Ext at 2000 F	B	2.00	126	99	58	34	63	-	1.27
EBN	Ext at 1700 F	A	2.09	141	126	75	27	45	25	1.[illegible]2
EBN	Ext at 1700 F	B	2.09	129	111	57	30	40	18	1.16
EBO	Ext at 1700 F	A	2.97	113	132	106	3	4	28-34	0.86
EBP	Ext at 1800 F	A	3.12	128	139	115	5	5	34	0.92
EBP	Ext at 1800 F	B	3.12	117	134	116	4	5	34	0.87
EBQ	Ext at 1900 F	A	3.89	← Fractured in Grips →					36	
EBR	Ext at 1800 F	A	4.04	80	134	127	← (3) →		35	0.60
EBR	Ext at 1800 F	B	4.04	← (4) →						
8776A	CD	AA	3.21	228	179	142	18	43	39	1.27
8776B	CD	B	3.21	181	159	100	27	43	32	1.14
8776C	CD	CC	3.21	203	155	112	21	47	34	1.31
8569A	CD	AA	2.55	234	178	151	18	38	38	1.31
8569B	CD	B	2.55	184	156	102	25	46	32	1.18
8569C	CD	CC	2.55	207	150	113	23	50	32	1.38
9533A	HR	AA	3.10	205	172	123	25	42	36	1.19
9533B	HR	B	3.10	189	162	111	25	44	34	1.17
9533C	HR	CC	3.10	200	158	111	24	47	35	1.26
9008A	HR	AA	2.64	198	161	114	27	48	34	1.23
9008B	HR	B	2.64	182	149	101	26	45	27	1.22
9008C	HR	CC	2.64	181	134	82	29	59	28	1.35
9176A	CD	AA	2.98	-	175	136	19	37	33	-
9176B	CD	B	2.98	-	151	86	31	46	25	-
9176C	CD	CC	2.98	-	177	138	19	36	32	-
9192A	CD	AA	2.87	-	171	135	19	40	36	-
9192B	CD	B	2.87	-	149	90	29	47	28	-
9192C	CD	CC	2.87	-	169	135	21	42	36	-
8686A	HR	AA	2.91	-	165	113	28	42	33	-
8686B	HR	B	2.91	-	157	102	28	44	30	-
8686C	HR	CC	2.91	-	166	116	26	41	33	-
9241A	HR	AA	2.88	-	165	112	29	45	33	-
9241B	HR	B	2.88	-	157	100	29	48	30	-
9241C	HR	CC	2.88	-	167	110	27	47	33	-
8921A	HR	AA	2.90	-	160	109	29	46	32	-
8921B	HR	B	2.90	-	155	100	28	46	30	-
8921C	HR	CC	2.90	-	163	111	26	45	33	-
9041A	HR	AA	3.08	-	169	119	27	46	34	-
9041B	HR	B	3.08	-	162	108	28	45	32	-
9041C	HR	CC	3.08	-	172	121	27	44	34	-

[3] Broke in shoulder.
[4] One specimen split during machining; second failed in threads at 116 ksi.

Table 2
Notched Tensile Test Results for Large Diameter Specimens

Material Code	Fabrication	Heat Treat-ment	Alumi-num WT %	Major Test Diameter D, in.	Notch Depth % ($\Delta d/D$ x 100)	Notch Radius in.	Notched Tensile Strength ksi	Notch-Strength Ratio
DZL	HR	A	2.92	1.875	49.1	FC[1]	196	1.19
DZL	HR	A	2.92	1.253	48.5	0.001	197	1.19
DZL	HR	A	2.92	0.752	51.1	0.001	189	1.15
DZS	CD	A	2.93	2.000	50.0	0.001	171	1.05
DZS	CD	A	2.93	1.875	56.4	0.001	174	1.07
DZS	CD	A	2.93	1.251	50.0	0.002	186	1.14
DZS	CD	A	2.93	0.746	50.6	0.001	187	1.15
EAH	30% CD	C	2.78	1.875	Broke in Fatigue			
EAH	30% CD	B	2.78	1.875	51.3	FC	171	1.10
EAH	30% CD	A	2.78	1.875	41.6	FC	224	1.21
EAH	30% CD	A	2.78	1.250	50.0	0.002	226	1.22
EAH	30% CD	A	2.78	0.750	50.0	0.001	237	1.28
EAL	HR at 2100 F	A	2.00	2.000	49.7	0.001	161	1.16
EAN	HR at 1700 F	A	2.00	1.875	56.1	FC	143	1.02
EAO	HR at 2100 F	A	2.97	2.000	52.8	0.006	91	0.61
EAM	HR at 1850 F	A	2.97	1.875	Broke in Fatigue			
EBM	Ext at 2000 F	A	2.00	1.875	46.0	FC	133	1.09
EBM	Ext at 2000 F	B	2.00	1.875	54.0	0.001	116	1.17
EBN	Ext at 1700 F	A	2.09	1.875	44.7	FC	142	1.13
EBN	Ext at 1700 F	B	2.09	1.875	54.8	0.001	113	1.02
EBO	Ext at 1700 F	A	2.97	1.875	55.5	0.002	63	0.48
EBP	Ext at 1800 F	A	3.12	1.875	Broke in Fatigue			
EBP	Ext at 1800 F	B	3.12	1.875	55.6	0.001	40	0.30
EBQ	Ext at 1900 F	A	3.89	1.875	Fractured in Grips			
EBR	Ext at 1800 F	B	4.04	1.875	Split During Machining			
EBR	Ext at 1800 F	A	4.04	1.875	55.2	Broke in Fatigue		

[1]Fatigue Cracked.

Table 3
Conditions for Fatigue Cracking of 1.875-Inch-Diameter Specimens

Material Code	Fabrication	Heat Treatment	Aluminum WT %	Applied Stress ksi	Yield Stress (0.2% Offset) ksi	Number of Cycles[1]	Result
EBN	Ext at 1700 F	A	2.09	45.5	75	21,000	Fatigue crack
EAH	30% CD	A	2.78	45.6	157	23,000	Fatigue crack
EAH	30% CD	B	2.78	45.6	99	22,000	Fatigue crack
EBM	Ext at 2000 F	A	2.00	42.3	72	14,000	Fatigue crack
EAN	HR at 1700 F	A	2.00	42.2	96	14,000	Fatigue crack
DZL	HR	A	2.92	43.7	123	22,000	Fatigue crack
EAH	30% CD	C	2.78	48.9	102	27,000	Failure
EBR	Ext at 1800 F	A	4.04	43.2	127	8,000	Failure
EAM	HR at 1850 F	A	2.97	43.1	112	10,000	Failure
EBP	Ext at 1800 F	A	3.12	42.1	115	6,[illegible]00	Failure

[1]Run at 470 rpm.

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Tensile and notch tensile properties of K-monel processed by different fabrication techniques were investigated. Material processed by standard hot rolling and cold drawing was found to meet the ductility and strength requirements of military specifications. A drastic (30%) final cold reduction, followed directly by aging, lowered the percent of elongation below requirements of military specifications, but did not lead to weakness or brittleness of notched specimens. Extruding of small ingots with insufficient reduction of area led to material with low strength and brittleness.

(Author)

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September 1965. 22 pp. Figs.
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(Over)

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